LCD DIFFRACTIVE ELEMENT DESIGN TO HANDLE MULTIPLE DISK THICKNESSES

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1. ABSTRACT

We describe the design of a single diffractive LCD element placed adjacent to the objective lens that can be addressed to provide the required spherical aberration (SA) compensation for a plurality of disk substrate thicknesses. It is now commonplace that optical disk drives must be able to handle disks of more than one substrate thickness. The major problem is compensating for the SA introduced when the highly corrected objective lens is used with a disk substrate thickness other than that which it was specifically designed for. An abundance of methods for solving this problem in the specific case of CD/DVD backward compatibility exist in the literature; we use an active device to extend this to include HD-DVD as well.

The LCD element acts as a switchable diffractive optical element. A set of electrodes defines the circular grating features that can be switched on or off to create diffractive lenses of the desired set of focal lengths. The liquid crystal modulates the phase and amplitude of the transmitted light according to the electrode pattern. We examine various approaches for the electrode layout that can implement 2-level, multi-level and continuous phase gratings in the LCD element. Two designs for the LCD wavefront compensator are presented that provide backward compatibility with DVD and CD formats from an HD-DVD system.

Keywords: multilayer disks, optical pickup head, CD/DVD, HD-DVD, LCD, diffractive optical element, optical disk storage

1. INTRODUCTION

With each new generation of optical disk storage, the optical system parameters, laser wavelength, disk thickness and the numerical aperture of the objective lens in particular, change to accommodate the increased information density on the disk. Backward compatibility with earlier formats is necessary to produce a commercially acceptable product. A major problem to solve is the compensation of spherical aberration (SA) introduced when the highly corrected objective lens is used with a disk substrate thickness and/or wavelength other than that for which it was specifically designed. An abundance of methods for solving this problem in the specific case of CD/DVD backward compatibility exist in the literature. Although the format is not yet fixed, the next generation of HD-DVD will use a blue laser, and likely also increase the lens NA and decrease the thickness of the disk substrate. At the same time, there is widespread interest in using multiple information layers, beyond the current two layers included in the DVD standard, for future disk systems. These new systems further complicate the problem of full compatibility.

Low voltage operation and low cost are two features that make liquid crystal devices (LCD) particularly attractive as optical modulators. Researchers have been investigating their application to amplitude and phase modulation in optical processing systems for more than a decade[1,2]. . LCDs have been used previously for wavefront correction and beamsteering[3,4] and have also been applied to optical disk systems. An early DVD pickup design by researchers at Sanyo used an LCD amplitude modulator to stop down the beam aperture giving a lower NA for reading CD disks[5]. In a different application, researchers at Pioneer utilized an LC panel to correct for aberrations caused by disk tilt[6].

This paper investigates the feasibility of using a diffractive LCD element placed adjacent to the objective lens that can be addressed to provide the required SA compensation for compatibility with HD-DVD, DVD, and CD disks. In the next section, we examine various types of LC devices and electrode structures and discuss their application to the present problem. In Sec. 3, we look at two specific design examples for LCD diffractive wavefront compensation devices that permit reading disks of

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any of the three formats, the first using the same wavelength for all three formats and the second using a separate wavelength for each format.

2. BACKGROUND AND DEVICE LAYOUT OPTIONS

The basic system layout being addressed is shown below in Fig. 1. An electrically addressable LCD modulator is placed in front of the objective lens. We assume that the objective lens has been optimized for an HD-DVD system using a 415nm laser source, 0.1mm disk substrate thickness and an NA of 0.8. The LCD modulator must provide amplitude modulation to stop down the NA of the lens and phase modulation to compensate for the spherical aberration induced by the DVD and CD disk thickness'.

2.1 LC Selection

Twisted nematic (TN) liquid crystals, such as those commonly used in display devices, produce amplitude modulation in a straightforward manner. The twist of the LC through the volume of the cell rotates the polarization of incident light by the amount of the twist. Placing the TN LC cell between crossed polarizers makes a simple amplitude modulator. The same device can also be used as a phase modulator, however Lu and Saleh[1] show that the phase and amplitude are coupled. This makes the TN cell a poor choice for wavefront correction.

Ferroelectric liquid crystals (FLC) can also be used for amplitude and phase modulation and have orders of magnitude faster switching times than nematic or twisted nematic cells.. Typically, an FLC cell is constructed as a half-wave retarder and an applied voltage rotates the birefringence axis. The specific FLC material determines the range of rotation. Amplitude modulation is accomplished by placing the cell between crossed polarizers. Phase modulation, on the other hand, uses circularly polarized light[2]. The amount of phase delay introduced is equal to twice the rotation angle of the FLC axis. Currently FLC materials are available that provide close to 90 degrees of rotation or a phase modulation range of roughly 180 degrees. As discussed in more detail below, binary 0° , 180° modulation can be used for a diffractive wavefront modulation device but the efficiency is poor compared to devices where 360° or more phase modulation is available. This range can be increased by cascading multiple FLC cells or by making two or more passes through the same cell. However, creating a diffractive lens with phase modulation distributed between multiple cells physically separated on the order of a millimeter is a design problem beyond the scope of this paper. Unlike TN cells, the phase modulation is pure with no associated amplitude modulation. Independent control of amplitude and phase modulation is most easily accomplished by cascading two FLC cells, using one for amplitude control and one for phase.

Homogeneously aligned nematic (HAN) liquid crystals also provide pure phase modulation. In the off state, the long (extraordinary) axis of the (uniaxial birefringent) LC molecules is typically parallel to the glass plates enclosing the cell, all molecules pointing in the same direction throughout the volume of the cell. When a voltage is applied between the two plates, the LC molecules tilt towards the direction of the applied electric field, the tilt amount being roughly proportional to the applied voltage. Phase modulation is accomplished using light polarized along the extraordinary axis. As the LC molecules tilt under applied voltage, the polarized light sees an index of refraction that varies continuously from n_e to n_o. The phase modulation is equal to $2\pi T\Delta n/\lambda$ where λ is the wavelength of the light, T is the LC cell thickness and Δn is the change in the index of refraction. Therefore the amount of phase modulation available from HAN LCDs can be set to multiple-π radians by controlling the thickness of the device. However, HAN LCD's are not configurable to provide amplitude modulation.

Therefore, for this application, a cascade of two LC layers is the most suitable arrangement, consisting of an amplitude modulator layer for stopping down the aperture, and a phase modulation layer to compensate for the SA due to differing substrate thickness. HAN LC is chosen for the phase modulation because it permits greater than 2π radians modulation range with a single LC layer. The amplitude modulator could be either TN or FLC, TN probably being the better choice since the same nematic LC material could be used for both phase and amplitude modulating layers by simply adding a 90° twist to the TN cell. The structure of the resulting LCD wavefront compensator is shown in Fig. 2.

2.2 Electrode layout

The electrodes determine the phase modulation profile. A significant range of modulation, many tens of π radians, is required to provide the necessary SA compensation. For this reason, direct refractive wavefront modification is not possible with a single thin LC layer. Instead, the standard diffractive optics approach is used whereby the desired phase profile is 'folded' by introducing discontinuities of 2π to keep the maximum phase range on the order of just a few π or less. Three candidate electrode styles are illustrated in Fig. 3. In the figure, the density of E-field lines in the LC indicates the relative strength of the E-field. The simplest type, a two-level phase grating, is shown in Fig. 3a. Transparent electrodes are deposited over the regions where an odd number of π modulation is desired. This is equivalent to a staircase approximation to the desired phase profile with each step having a phase height of π radians. While this gives a very simple form to the electrodes, it places a severe limitation on the light efficiency. It is well known from diffraction theory that a rectangular grating of this type can, at best, achieve 41% diffraction efficiency into the desired +1 order. Furthermore, since the light passes through this element twice, once on the way to the disk and a second time after reflection from the disk, this element utilizes only about 16% of the light, the rest going into unused diffraction orders.

A better option in terms of efficiency is shown in Fig. 3b. In this arrangement, each 2π phase range is divided into multiple steps, with a separate electrode for each step. Using four steps as shown in Fig. 3b, the efficiency is doubled compared to the 2-level grating of Fig. 3a. This quadruples the efficiency of the element when the double pass through the element is taken into account giving an overall efficiency on the order of 64%. Further increasing the number of phase steps will increase the efficiency but at a diminishing rate. For example, increasing from four to eight phase steps will boost the single pass theoretical efficiency only by a factor of approximately 1.1. Therefore, four steps seems to an optimum compromise between efficiency gain and increased electrode complexity. The number of steps that are practical is limited by the minimum electrode width that can be implemented. Since two addressable gratings are to be multiplexed within the electrode pattern for this application, one for DVD compatibility and one for CD compatibility, this will further impact the required minimum electrode width. Klaus et. al.[4] describe a wavefront modulator using a nematic LC supplied by Merck Japan Ltd. that has a birefringence of 0.29. With this LC, a phase modulation range of 2π requires an LC thickness of >1.5 microns @λ=415nm and an LC thickness of >2.7microns @λ=780nm. A minimum electrode zone width on the order of 5 microns should be sufficient to clearly define the distinct E-field regions within the LC.

A third alternative is shown in Fig. 3c. Klaus et. al.[4] introduced the concept of "superelectrodes" for an LC wavefront modulator where they applied it to beamsteering and adaptive microlenses for a Shack-Hartmann wavefront sensor. The superelectrode consists of a number of thin discrete transparent electrodes deposited at uniform positions across a region or zone of the LC device. The discrete electrodes are joined outside of the active optical area by a distributed resistive divider (e.g. opaque thin metal) into groups that form the superelectrodes. When a voltage is applied at each side of the superelectrode, a linear voltage gradient is created impressed across the corresponding LC region creating a continuous phase grating. This is equivalent to increasing the number of phase steps in the arrangement of Fig. 3b but, in some cases, results in a simpler driver. Since the discrete electrodes making up the superelectrode are intended to act together to create a phase gradient, the minimum electrode width can be reduced to whatever is lithographically feasible. Klaus et. al. used 2 micron electrode widths and reported that, if the separation between two discrete electrodes in a superelectrode bundle was $\pi/5$ or less in phase, then there was no significant difference with a continuous grating. In an actual device, they were able to achieve efficiencies greater than 90%.

The final question to be addressed is that of multiplexing two or more application-specific sets of electrodes onto a single device. In general, the desired electrode patterns are unrelated. While there is some freedom to scale the phase response when the superelectrode approach is used (see the first example below), even for functionally related phase profiles, the diffractive element approach creates 2π phase zones that overlap in an irregular manner. Therefore, the electrodes must be deposited in such a way that each application can be addressed independently. The basic approach is shown in Fig. 4. The electrode patterns for each application are computed separately. When electrodes from two applications overlap, a third set of electrodes is created in the overlap areas. In Fig. 4a, electrodes from application X and application Y are seen to overlap. Electrode "w" is created in the overlap area and shared by the two applications applying power to electrodes X' and w for application X (Fig. 4b), and applying power to electrodes Y' and w for application Y (Fig. 4c).

3. DESIGN EXAMPLES

3.1 Example 1: HD-DVD, DVD, CD compatibility using same wavelength

We first designed an NA 0.8 system at λ=415nm wavelength with a lens radius of 2.45mm, working distance of 1.51mm and disk substrate thickness of 0.1mm to represent the HD-DVD system. The lens design was performed with Zemax optical design software[7]. For this first example, we assume that the same laser source will be used for all disk formats and designed the LCD element to provide wavefront compensation to give the same spot size on the disk as in standard DVD and CD systems. Since spot size is proportional to λ/NA, the effective NA for the DVD and CD systems are small due to the use of the blue wavelength. Direct scaling by wavelength gives NA=0.38 for the DVD system and NA=0.24 for the CD system. As a result, the compensated lens radii were 1.1mm for DVD and 0.7 mm for CD. These apertures are straightforward to implement using either the TN or FLC amplitude modulator methods described in the previous section. Standard disk thickness of 0.6mm for DVD and 1.2mm for CD were assumed and the working distances of the two systems are 1.25mm for DVD and 1.0mm for CD. The calculated phase profiles to produce diffraction-limited spots on the disks are shown in Fig. 5a.

The steeper phase profile of the CD system means that the mod 2π phase zones will be narrower for this system. The minimum zone width is calculated to be 30 microns. This is large enough that both the multi-level grating approach of Fig. 3b and the superelectrode approach of Fig. 3c can be considered. It turns out that the phase profiles for the NA 0.38 DVD system and the NA 0.24 CD system are scaled versions of eachother to within $\lambda/15$ peak variation using a scale factor of 3.61226. (i.e., max[(3.61226 x phase (0.38 system) – phase (0.24 system)] < $\lambda/15$.) This relationship makes the use of the superelectrode approach attractive.

The superelectrodes are designed to fit the 2π phase zones of the CD system. One side of the superelectrode is attached to ground and the other to the voltage that corresponds to 2π phase. The DVD system will use the same superelectrodes within the CD system aperture augmented by a set of superelectrodes to fill out the DVD system aperture that fit the 2π phase zones of the DVD system. Since the phase profiles are related by scale, one might at first be tempted to directly scale the CD voltages for the DVD system. This wouldn't work since the phase discontinuities would no longer be 2π multiples. Instead, the modulator must be made thick enough to support up to 4π phase range (in general) and the applied voltages take on analog values such that the phase discontinuities are multiples of 2π. The following table shows the positions and the necessary phase levels for this example. The diffractive 'folded' phase profile for the CD and DVD systems when the same set of superelctrodes are used is shown in Fig. 6. The phase curvatures of the individual zones, particularly the first superelectrode zone can be implemented with a slightly nonuniform spacing of the discrete electrodes making up the superelectrode. The DVD phase profile is no longer the customary uniform sawtooth associated with most diffractive optical elements. It becomes apparent that the simplification offered by directly using the same set of superelectrodes for both DVD and CD systems comes at the cost of a more complicated electronic driver requiring a rather large set of analog voltages.

Table 1: positions and phase levels for the superelectrodes for example # 1

Superelectrode #	Superelectrode position (μm)	NA0.24 Amplitude/Phase	NA0.38 Amplitude/Phase
1	0 - 185	1.0 / 0 - 2π	1.0/ 0 - 1.77338
2	186 - 263	1.0 / 0 - 2π	1.0/ 1.77338 - 3.54799
3	264 - 323	1.0 / 0 - 2π	1.0/ 3.54799 - 5.30709
4	324 - 374	1.0 / 0 - 2π	1.0/ 5.30709 – 7.05990
5	375 - 420	1.0 / 0 - 2π	1.0/ 0.776717 - 2.55161
6	421 - 461	1.0 / 0 - 2π	1.0/ 2.55161 - 4.28146
7	462 - 500	1.0 / 0 - 2π	1.0/ 4.28146 - 6.05007
8	501- 536	1.0 / 0 - 2π	1.0/ 6.05007 – 7.78391
9	537 - 570	1.0 / 0 - 2π	1.0/ 1.50072 - 3.22288
10	571 - 603	1.0 / 0 - 2π	1.0/ 3.22288 - 4.96875
11	604 - 634	1.0 / 0 - 2π	1.0/ 4.96875 – 6.67176
12	635 - 664	1.0 / 0 - 2π	1.0/ 0.388576 - 2.09123
13	665 - 694	1.0 / 0 - 2π	1.0/ 2.09123 - 3.78494
14	695 - 735	0.0 / --	1.0 / 3.78494 - 2π
15	736 - 834	0.0 / --	1.0 / 0 - 2π
16	835 - 929	0.0 / --	1.0 / 0 - 2π
17	930 - 1021	0.0 / --	1.0 / 0 - 2π
18	1022 - 1114	0.0 / --	1.0 / 0 - 2π

3.2 *Example 2: HD-DVD, DVD, CD compatibility using customary wavelengths for the media*

In this example, the same system parameters as the first example are used with the exception that we now assume the customary wavelengths for each medium, i.e., 415nm for HD-DVD, 650nm for DVD, and 780nm for CD. This may be required, for example, in a HD-DVD drive that supports backward compatibility with DVD-R and CD-R media. In this case, the system NA's also assume the customary values of 0.6 for the DVD system and 0.45 for the CD system. Again the aperture stops are implemented using either TN or FLC amplitude modulation as indicated in Fig. 2. The desired phase profiles are shown in Fig. 5b. In this case, the phase profiles are not proportional to each other, as can easily be seen. For contrast with the first example, we look at the feasibility of implementing the multiplexed LCD compensator using a four-level grating approach. The mod 2π diffractive phase profiles are shown in Fig. 7. The profile for the NA 0.6 system has been reflected across the origin in the figure to make viewing and comparison simpler.

We wish to implement these two profiles with four-level step approximations. The minimum 2π phase zone occurs in the CD system compensator and is equal to approximately 40 microns, easily sufficient to split into four levels. Table 2 shows the data for where the phase steps should be when the two systems are considered independently. (The electrodes for the two systems multiplexed on one device must include a third set of shared electrodes for the overlap regions. From the table, it can be seen that these shared electrodes may need to be switched between any of the four phase levels. It can also be seen that some of the shared electrodes will be as narrow as 2 microns. This poses no challenge to modern lithography. The step widths, on the other hand, will be much wider – 10 microns minimum – since the shared electrodes are never used alone.

Table 2: Positions of the phase steps for a four-level grating wavefront compensator for the NA 0.45 and NA 0.6 systems of example #2. A third set of shared electrodes must be fabricated in the areas where the two systems overlap. All units are in microns. (Blank rows in the NA 0.6 system are simply for convenience in comparing the positions with the NA 0.45 system.)

NA 0.45 level 0	NA 0.45 level $\pi/2$	NA 0.45 level π	NA 0.45 level $3\pi/2$	NA 0.60 level 0	NA 0.60 level $\pi/2$	NA 0.60 level π	NA 0.60 level $3\pi/2$
0-119	119- 168	168-206	206-238	0-165	165 -234	234-287	287-333
238-267	267-293	293-317	317-339				
339-360	360-380	380-399	399-417	333 -373	373-409	409-443	443-475
417-435	435-452	452-468	468-484				
484-500	500-515	515-530	530-545	475-505	505-534	534-562	562-589
545-559	559-573	573-586	586-600				
600-613	613-626	626-639	639-652	589-614	614-639	639-664	664-688
652-664	664-676	676-689	689-701				
701-713	713-724	724-736	736-747	688-711	711-734	734-756	756-779
747-759	759-770	770-781	781-793				
793-804	804-815	815-825	825-836	779-800	800-822	822-843	843-864
836-847	847-858	858-868	868-879				
879-889	889-899	899-910	910-920	864-885	885-906	906-926	926-947
920-930	930-941	941-951	951-961				
961-971	971-981	981-991	991-1001	947-967	967-987	987-1007	1007-1027
1001-1011	1011-1021	1021-1031	1031-1040				
1040-1050	1050-1060	1060-1070	1070-1080	1027-1047	1047-1067	1067-1087	1087-1107
1080-1089	1089-1099	1099-1109	1109-1118				
1118-1128	1128-1138	1138-1148	1148-1157	1107-1128	1128-1148	1148-1168	1168-1188
1157-1167	1167-1177	1177-1186	1186-1196				
1196-1205	1205-1215	1215-1225	1225-1234	1188-1209	1209-1229	1229-1250	1250-1271
1234-1244	1244-1254	1254-1264	1264-1273				
1273-1283	1283-1293	1293-1302	1302-1312	1271-1292	1292-1314	1314-1336	1336-1358
1312-1322	1322-1332	1332-1342	1342-1352				
1352-1361	1361-1371	1371-1381	1381-1391	1358-1380	1380-1403	1403-1427	1427-1451
				1451-1476	1476-1501	1501-1528	1528-1555
				1555-1584	1584-1615	1615-1647	1647-1683
				1683-1722	1722-1767	1767-1823	1823-1840

4. CONCLUSION

We have demonstrated that it is feasible to design an active LCD wavefront compensation device that can enable a disk drive to handle many different disk formats with the same objective lens. The paper lays out the basic design concepts in terms of type of liquid crystal and options for laying out the electrodes. Two examples were presented of full designs for the LCD element that will compensate the wavefront of a system designed for HD-DVD so that it can also be used for DVD and CD disk formats. The first example assumed the same wavelength was used for all three systems. The wavefront compensator was designed using the superelctrode concept introduced in [Ref. 4] and shown in Fig. 3c. The second example used a different wavelength for each HD-DVD, DVD and CD. A 4-level grating design was described. Both appear to be viable design approaches, however testing needs to be done to verify that these systems can achieve the necessary wavefront accuracy for this application. Other applications can also be considered such as an active compensation device that greatly increases the number of disk layers that can be read.

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5. REFERENCES

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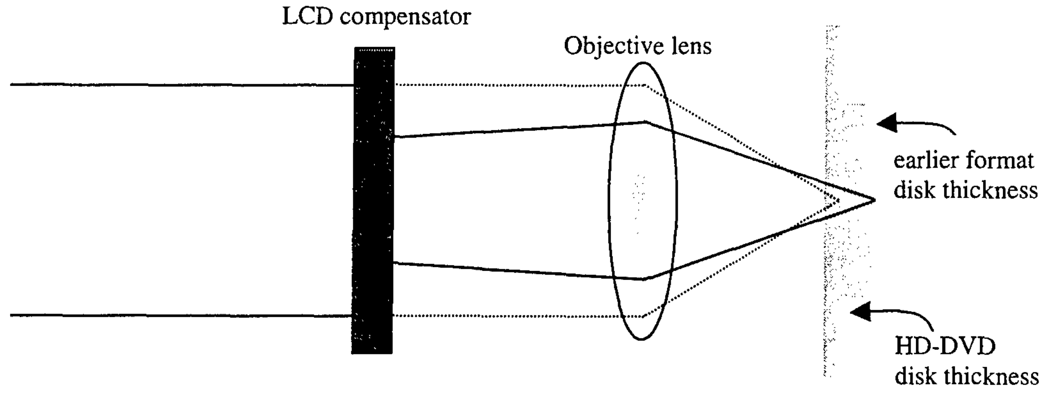


Fig. 1: Basic system configuration

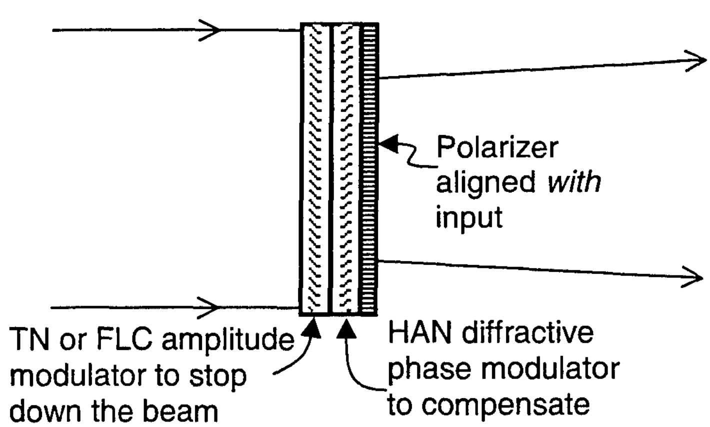
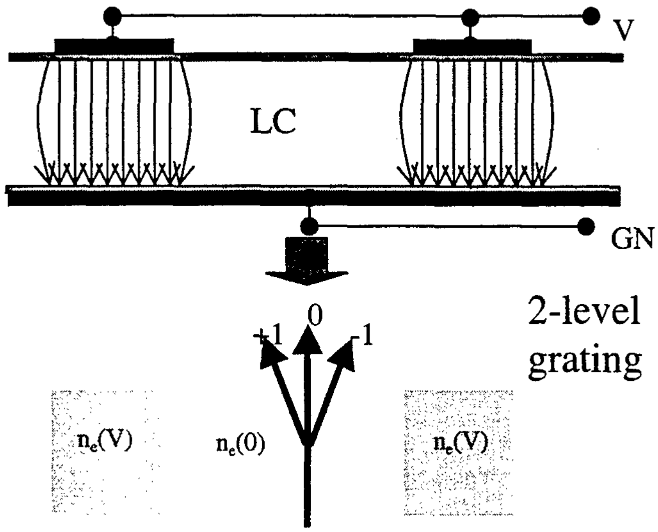
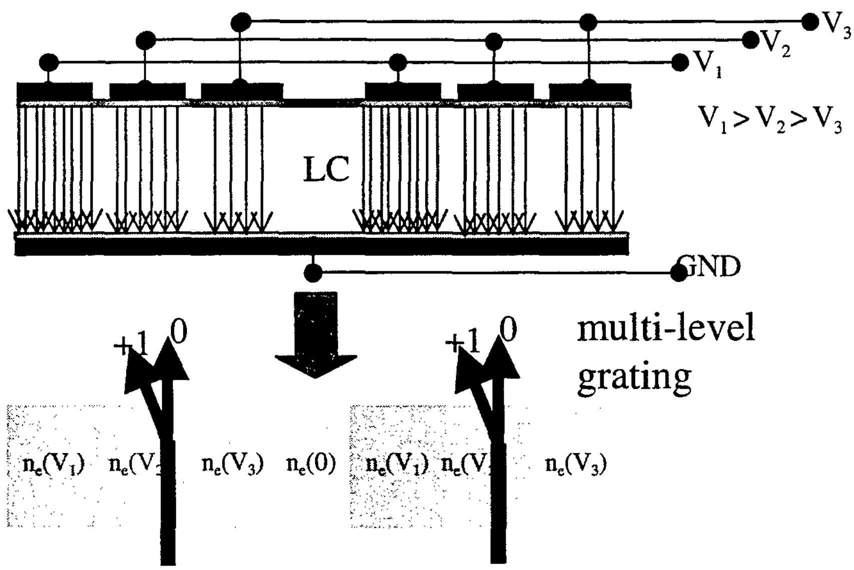


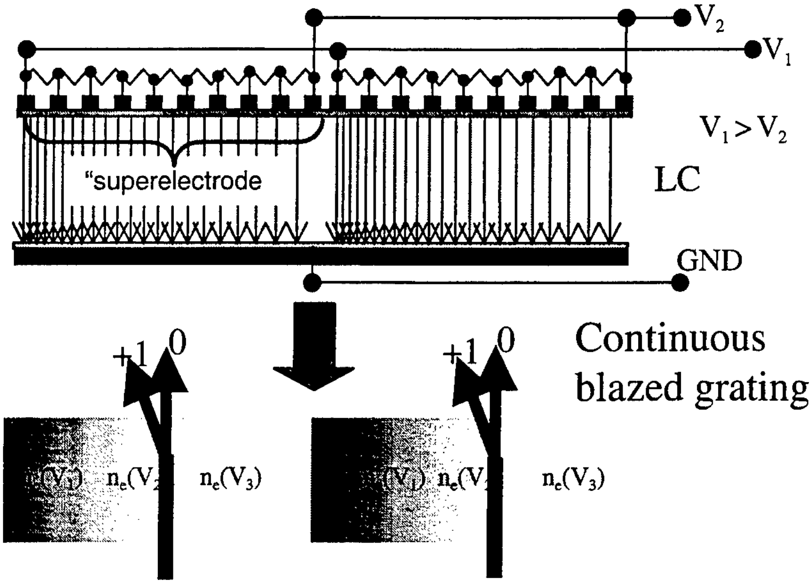
Fig. 2: Structure of the LCD wavefront compensator


V
LC
GN
+1
0
-1
2-level
grating
$n_e(V)$
$n_e(0)$
$n_e(V)$

(3a)


V_3
V_2
V_1
$V_1 > V_2 > V_3$
LC
GND
+1
0
+1
0
multi-level
grating
$n_e(V_1)$
$n_e(V_3)$
$n_e(0)$
$n_e(V_1)$
$n_e(V_3)$

(3b)



(3c)

Fig. 3: Three types of electrode layout to implement diffractive LCD element. (a) 2-level binary grating (b) multilevel binary grating, (c) continuous blazed grating using "superelectrodes"

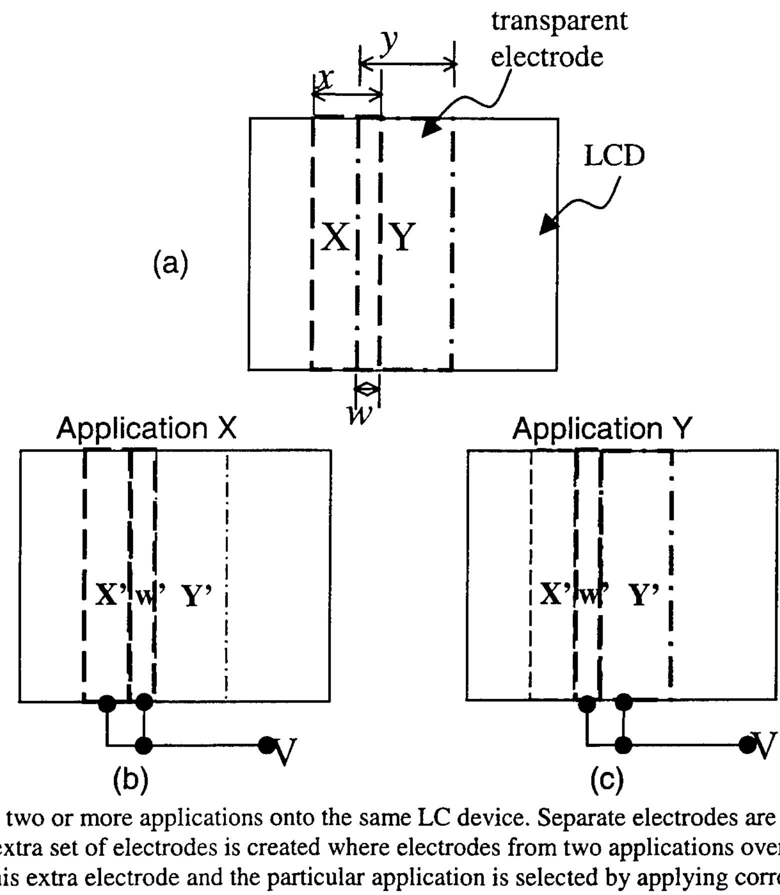


Fig. 4: Multiplexing two or more applications onto the same LC device. Separate electrodes are required for each application. (a) An extra set of electrodes is created where electrodes from two applications overlap. The two applications share this extra electrode and the particular application is selected by applying correct application of the driving voltage.

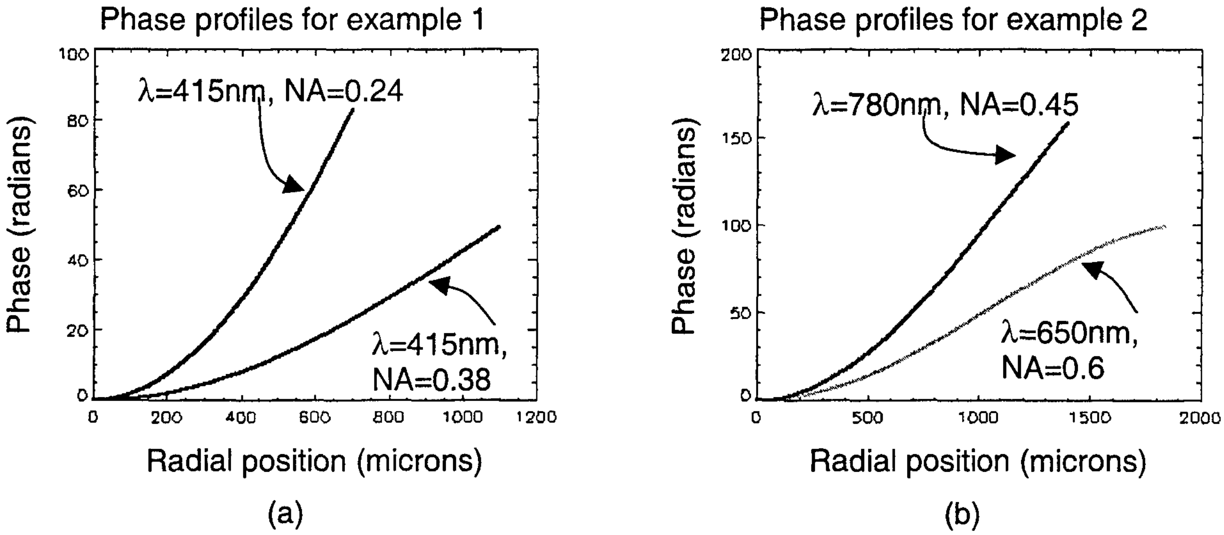


Fig. 5: Desired phase profiles for the LCD diffractive compensator. (a) Example 1 – same wavelength for HD-DVD, DVD, and CD, (b) Example 2 – HD-DVD uses λ=415nm, DVD uses λ=650nm, CD uses λ=780nm

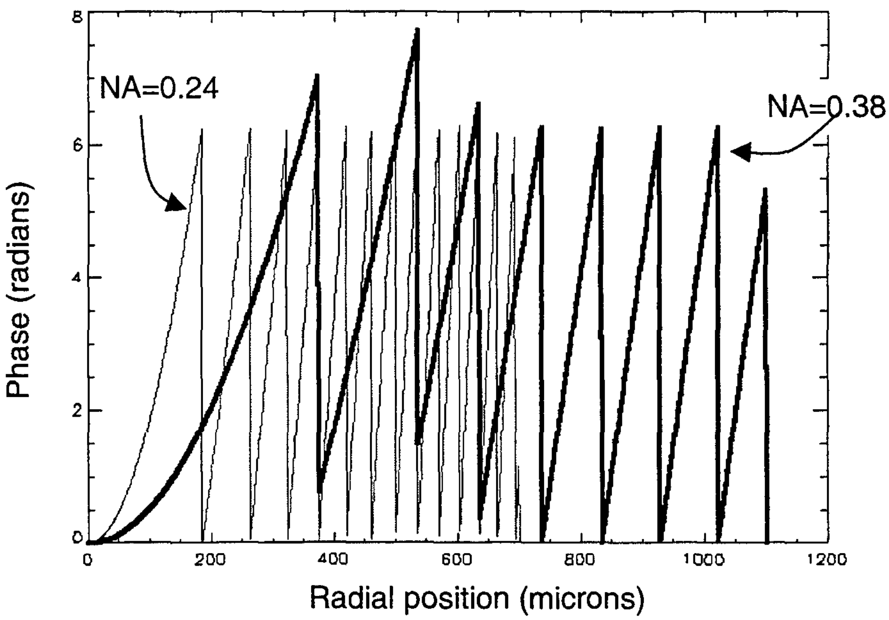


Fig.6: Diffractive phase profile for NA 0.38 compensator when the superelectrode pattern from the NA 0.24 system is directly used.

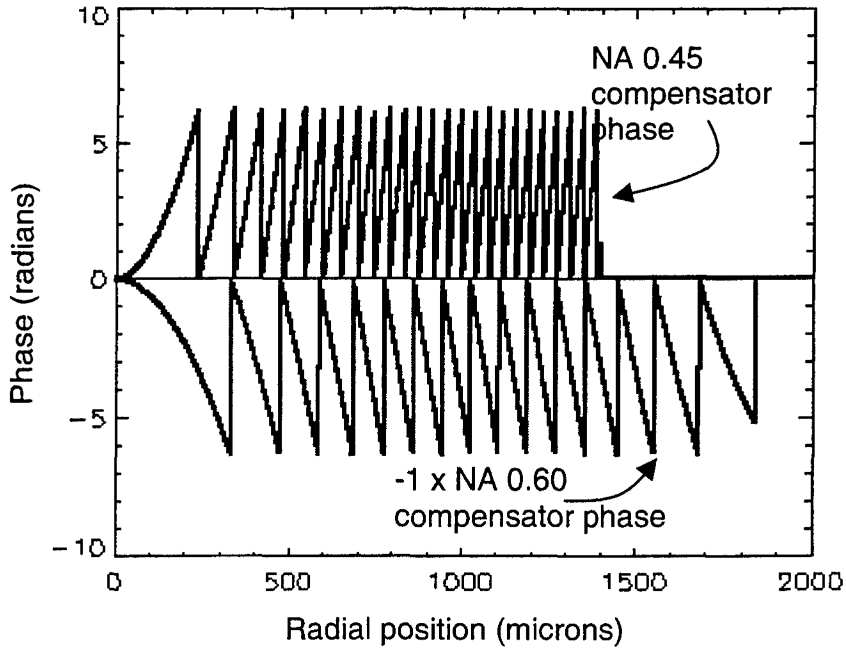


Fig. 7: Ideal diffractive phase profiles for the NA 0.45 and NA 0.6 wavefront compensator devices. The phase profile for the NA 0.6 compensator has been multiplied by -1 to make it more easy to view.